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1 Summary

We have developed an ultrafast optical nonlinear spectroscopy facility with the motivation of studying spatio-temporal soliton interactions for all-optical switching application and several associated nonlinear optical process. The facility has been built with \$200K of support from the DURIP program (F49620-97-1-0436) and approximately \$103K from the AFOSR (F49620-96-1-0431) and \$93K of matching money provided by the University of Colorado. This report provides complete technical details of the ultrafast optics facility and describes the ongoing experiments.

The entire proposed statement of work regarding the development of an ultrafast laser facility has been successfully completed. The lab can support several nonlinear optical experiments simultaneously and currently hosts a graduate student working towards a doctoral degree on spatial soliton switching with 2+1D solitons. In addition we are currently in collaboration with a small local optics company, Perdix Inc., on a project of mutual interest for the development and characterization of a nonlinear optical material using discotic liquid crystals.

The Ultrafast Optics Lab consists of a >20GW peak power sub-50fs 1KHz pulsed amplified Ti:sapphire laser system. The laser system consists of a Ti:sapphire oscillator, a Nd:YLF CW pump laser, a regenerative Ti:sapphire amplifier and a Nd:YAG pulsed pump laser. This system is followed by an optical parametric amplifier to enable the ultrashort pulse center frequency to be continuously tuned from 580nm to 2200nm in order to explore non-linear response in the broad spectral range. Complete computer controlled tunable ultrafast pulses allow unprecedented experimental flexibility for ultrafast nonlinear spectroscopic characterization and all-optical soliton switching experiments with several different materials. The facility developed also includes several linear and nonlinear pulse characterization and automation tools including CCD-based and scanning-grating spectrometers, a polarimeter, an automated multi-axis motor controller, several autocorrelators, frequency resolved optical

gating (FROG) pulse characterization , and a tilted front pulse autocorrelator.

2 Statement of Work and Final Progress Report

We proposed to develop a highly flexible, multi-user ultrafast laser facility for experimental characterization of nonlinear optical materials over a wide range of wavelengths. Our proposed plans to purchase the ultrafast laser system and the diagnostic tools are enumerated below along with their completion status.

1. CW Pump laser

Proposed. A CW pump laser is required to provide the seed power for the Ti:Sapphire laser. This laser can be either a gas Ar^+ ion laser or a solid-state Nd:YLF laser. The solid state lasers have lower powers but better mode quality, pointing stability, and longer lifetimes, and are considered to be the superior choice for this application. Coherent and Spectra-Physics each offer 5W versions of this type of laser, with the Coherent Verdi costing \$55,000 with single-frequency performance, and the Spectra-Physics Millennia costing \$50,000 without single-frequency operation. The DURIP will fund \$45,000 towards this CW pump source, with the remainder funded from the University matching funds. The useful life of this laser is at least a decade since it is all solid state, but the diodes may need to be replaced every few years.

Status: Complete. After comparing the stability of diode pumped solid-state technology with the the ion lasers, we decided on and purchased a 5W Millennia laser from Spectra-Physics as a pump source for Ti:Sapphire oscillator. The Millennia is a multi-line laser with good beam pointing stability for pumping Ti:Sapphire oscillators. A Millennia laser operating at 3.0W has the same performance for the oscillator as an ion laser operating at 5.0W. Coherent Verdi offers a single line performance at a higher cost which is not necessary for our purpose, although this provides some versatility for

purposes other than pumping.

2. Ti:Sapphire Laser System

Proposed. A femtosecond laser source is required for these experiments, and will be provided by a Kerr-lens modelocked Ti:Sapphire system. Though we have constructed a laser of this type in our laboratories that has the capability of producing sub 20fsec pulses, its operational stability is suspect and a commercial system will be much more versatile and dependable. A system such as the Mira Basic 900-B from Coherent for \$46,500 would have the minimum performance required to accomplish the items in the statement of work, while a system such as the Mira 900-F for \$86,500 would provide more flexibility in terms of wavelength range and laser diagnostics. Another option would be the Spectra-Physics 3941-S1S modelocked Ti:Sapphire system for \$53,000. Finally, it should be mentioned that by the time of the DURIP awards, a new technology of direct diode-pumped Cr:LiSaF lasers will become commercially available, and will be evaluated as another option. In any case, the DURIP contribution to the Ti:Sapphire laser system will be the price of the basic Mira 900-B \$46,500, with any additional funding required for upgraded models to be supplied by the University Matching funds. The useful life of this laser is at least a decade.

Status: Complete. Tsunami, from Spectra-Physics, and the oscillator kits from Stingl, and KML are the commercially available Ti:Sapphire Kerr-lens mode-locked oscillators which produces pulses as short as 35fs or lower. A similar laser from Coherent and the all fiber oscillator from Clark Instruments produce pulses of 70fs width and are not suitable for our purpose. The oscillator kits which produce short pulses require considerable day-to-day adjusting while the Tsunami system is a turn key system with acceptable temperature tolerances. For the general long term stability and keeping in view the day-to-day performance and its short pulse width we preferred Tsunami over the other oscillators.

3. Regenerative Amplifier

Proposed. A typical regenerative amplifier such as those manufactured by Clark instruments, Positive Light (resold by Spectra-Physics), or Photonics Industries, costs approximately \$75,000. Half of this cost will be paid for from existing AFOSR funding, with \$38,000 of this item funded by the DURIP award. The useful life of this laser may approach a decade.

Status: Complete. The Spitfire, a regenerative amplifier seeded by the Tsunami was purchased. The amplifier system is a sub 50fs version. Quantronix also sells a sub-50fs system, but it is a multi-pass amplifier and the spatial pulse profiles are known to be better with a laser amplifier system with a cavity configuration as opposed to a multi-pass system. Multi-pass systems have the advantage of producing better post-pulse characteristics since they do not operate on the principles of amplifier cavity feedback. However, the post-pulses from regenerative amplifiers are not usually a problem for ultrafast interactions since the time separation usually is very large in comparison to the pulse duration. Further, in a well-aligned amplifier cavity like the Spitfire we purchased, the extinction ratio is quite good. We found the Clark-MXR does not meet our pulse-width requirement, Coherent/BMI has low mode quality, and the Quantronix multi-pass system has surprisingly low pulse contrast. The Spitfire met all of our needs.

4. Pulsed pump laser

Proposed. A typical KHz-repetition rate Nd:YAG or Nd:YLF pump such as those manufactured by Clark instruments, Positive Light (resold by Spectra-Physics), or Photonics Industries, costs approximately \$65,000 and is required to pump the regenerative amplifier. Half of this cost will be paid for from existing AFOSR funding, leaving \$33,000 to be paid for by this DURIP award. The useful life of this laser is at least 5 years and hopefully longer, but the flash lamps will need to be replaced periodically.

Status: Complete. The Merlin, a Nd:YLF flash-lamp-pumped pulsed-pump laser was purchased from Spectra-Physics. This is the standard pump laser for the Spitfire regenerative amplifier. An ideal pump is a solid-state pumped Q-switched pulsed system since flash lamps have short operational lifetimes. At the time of purchase this technology was not available. The performance of the regenerative amplifiers are rated based on the compatible pumps which the companies sell as a package. We preferred the Merlin because the Merlin-Spitfire combination best suited to our needs.

5. Optical parametric amplifier (OPA)

Proposed. The OPA is used to shift the wavelength of the femtosecond pulses from the near IR (750-1050nm) to the mid IR (1.0-2.0 μ m) where strong low-loss nonlinearities and anomalous dispersion are readily available in our candidate materials. In combination with a frequency doubler or white light continuum generator, the visible spectrum can be covered as well. Various manufacturers such as Clark, Coherent, CSK, and Spectra-Physics produce systems with a wide range of costs and features, but a typical system such as the Clark ORC-1 costs \$27,500, while the Spectra-Physics system is listed as \$35,000. This will be paid for from the AFOSR grant (budgeted cost of \$29,000), but will be an important component of the DURIP ultrafast spectroscopic laser facility. The useful life of this equipment approaches a decade.

Status: Complete. The TOPAS, manufactured by Light-Conversion Ltd (resold by Quantronix) is a traveling-wave parametric amplifier which is compatible with the Spitfire regenerative amplifier. We selected this system for several reasons. Other tunable systems (OPO) are oscillator based and they were not preferred because of their lower tuning range and longer pulse width. The TOPAS meets all our requirements of energy, pulse width and broad tuning range. Being an amplifier system as opposed to an OPO, the system can be modified for lower input pulse energies by replacement of a few optical components and can also produce various pulse widths up to the picosecond

regime. Clark IR-OPA, BMI Venturi and Spectra-Physics 800-1-USP, either fall short of tuning range, pulse energy or pulse width requirements. In addition all occupy much more research space than the compact TOPAS.

6. Autocorrelator

Proposed. A nonlinear autocorrelator will be required for femtosecond pulse characterization. A commercial system such as the Femtochrome FR-103XL/KDP scanning autocorrelator or the INRAD 5-14B cost \$8500. This will be funded from the AFOSR grant and the University Matching funds. The useful life of this equipment approaches a decade.

Status: Complete None of the commercially available scanning autocorrelators were suitable for handling very short femtosecond pulses (sub 20fs), simultaneously meeting the needs of flexibility, low linear and dispersion related error. Therefore we decided on building the autocorrelator in-house. We have constructed a scanning-speaker-cone autocorrelator and a rotating-mirror autocorrelator/cross-correlator. The rotating-mirror system has ultrafast optics for low dispersion and the rotating mirror delay produces very low nonlinear error.

In addition, we purchased a tilted front pulse autocorrelator (TFPA) from Light Conversion Ltd., for the purpose of characterization of spatially chirped optical pulses. To our knowledge, the TFPA is the only instrument of its kind available commercially.

7. Frequency resolved optical gating

Proposed. Frequency resolved optical gating (FROG) characterization systems offer even more powerful ultrafast pulse characterization capabilities than autocorrelators. We plan to acquire a FROG-basic system without the analysis software from Clark Instruments for \$16,000. We will write our own analysis software. The useful life of this equipment is at least a decade.

Status: Complete The FROG system from Positive-Light is better designed and implemented than the Clark Instruments FROG. Further, Clark was planning on withdrawing support to the FROG system they were marketing. Femtos sells a SHG FROG which is four times more expensive than the Positive-Light FROG. SHG doesn't give complete time-spectral information about the ultrashort pulses and has time direction ambiguities. The only advantage of a SHG-FROG is the sensitivity. Polarization gating FROG requires more energy but doesn't have any ambiguities. The Spitfire amplifier has high pulse energies and can easily allow PG-FROG measurements. Hence we purchased a Positive-Light polarization gating FROG system which is compatible with the Spitfire regenerative amplifier.

8. Spectrometer

Proposed. We currently have a simple, low resolution, visible and near IR (400-1100) spectrometer (Ocean Optics S1000) which is useful for aligning a Kerr-lens mode-locked laser. The FROG system includes another imaging spectrometer with low dynamic range. However, for nonlinear materials characterization we will require a much higher resolution, higher dynamic range, and wider wavelength range fully calibrated scanning spectrometer such as the Hewlett-Packard HP71450A which lists for \$36,700. With the 10% HP academic discount this is expected to cost \$33,030 with half of this cost funded from DURIP (\$16,500) and half funded by the University Matching funds. The useful life of this equipment is at least a decade, and probably significantly longer.

Status: Complete We have examined several companies which produce commercial optical spectrum analyzers. Hewlett Packard and Anritsu corporations produce spectrum analyzers which span a limited large wavelength range of 650nm to 1700nm. Advantest and Ando corporation spectrum analyzers were the only ones which have a large span of 350nm-1750nm. However, Ando's instrument is also capable of producing a wavelength reproducibility of 0.005nm in 1 minute and measurement level range from

-65dBm to 20dBm. In addition to purchasing an Ando scanning spectrum analyzer, we also purchased an imaging spectrometer from ARC. The imaging spectrometer is a very versatile instrument which can be used as a multichannel spectrometer. The imaging capabilities can be utilized in building a FROG. ARC has detection system limited imaging resolution and is well-suited for our application. In comparison with ISA and CVI imaging systems, ARC has better imaging resolution specifications.

9. Polarization stokes meter

Proposed. A polarization Stokes meter provides the full vectorial characteristics of an optical beam. Stokes meter systems are produced by Hewlett-Packard (HP8509A \$33,000), Instrument Systems (RPA2000 \$50,000), and Gaertner Scientific (Stokesmeter \$17,200). We have budgeted \$17,200 for the Stokesmeter to be paid for by the University matching funds. We may elect to acquire one of the more expensive models with additional funding from the NSF young investigator award, or alternatively to build our own specifically tailored for ultrafast time resolved polarization measurement applications

Status: Complete We purchased a Thorlabs polarization Stokes meter. Thorlabs polarization Stokes meter is a better alternative to all the the other expensive models.

10. Tunable acoustooptic filter

Proposed. A tunable acoustooptic filter (TAOF) allows the rapid electronic phase or spectral filtering of an ultrashort pulse to produce an ultrafast shaped pulse. Appropriate TeO_2 TAOF devices are produced by Inrad, Isomet, AOTF Inc, and NEOS. Typical commercial devices command prices of \$5500-8500, but since we often design and custom AO devices of much higher performance and for lower cost, we expect to pay only \$5000. The useful life of this device will approach a decade.

Status: Abandoned. We explored several tunable acoustooptic filters for the purpose of ultrafast pulse shaping, and concluded that none of the commercially available devices were suitable to our bandwidth requirements.

We have also purchased the following additional equipment not mentioned in the earlier proposed list.

- **Auto-Optics motion control system Proposed.** We purchased a highly flexible computer-programmable two axis, encoded motor control system for automation of nonlinear experiments and nonlinear instruments.

3 Introduction

The KAOS Ultrafast Optics Lab facility has been developed for nonlinear optical material characterization and all-optical ultrafast logic device testing using funds from the DURIP program (0996.01.1175B). The lab can be used for several nonlinear material characterization experiments like Z-scan, FROG, transient grating, transient 4WM, pump-probe spectroscopy, and coherent transients. Our primary interest is the generation and interaction of optical solitons for ultrafast switching. The most important property for ultrafast optical soliton dragging interactions is the Kerr coefficient, which can be measured with the Z-scan technique in a wide spectral range with the current facility. The ultrafast laser system is capable of producing sub 50fs high peak power laser pulses which can be tuned to any center wavelength between 580nm-2200nm. To achieve this a stable short < 35 fs Ti:Sapphire pulses are amplified with a regenerative amplifier and the amplified pulses are used to pump a parametric amplifier, which produces tunable radiation.

Complete characterization of the laser pulses presents an interesting challenge, due to their short pulse width. A combination of linear and nonlinear tools are required for this purpose. The lab has several diagnostic tools like spectrometers, polarimeters, autocorrelators, and FROG. These diagnostic tools are also very helpful in day-to-day system alignment.

This report describes the ultrafast optics facility and the ongoing experiments in the lab.

4 High power tunable ultrafast laser System

The KAOS Ultrafast Optics Lab comprises of a >20 GW peak power sub 50fs Spectra-Physics Ti:Sapphire laser system which pumps a tunable ultrashort four stage optical parametric amplifier of superfluoresence (TOPAS, Quantronix) tunable from 580nm to 2200nm. High energy, $>800\mu\text{J}$, 44fs pulses are produced by a Spitfire regenerative amplifier which uses chirped pulse amplification to amplify stable but low power sub 35fs seed pulses from a kerr-

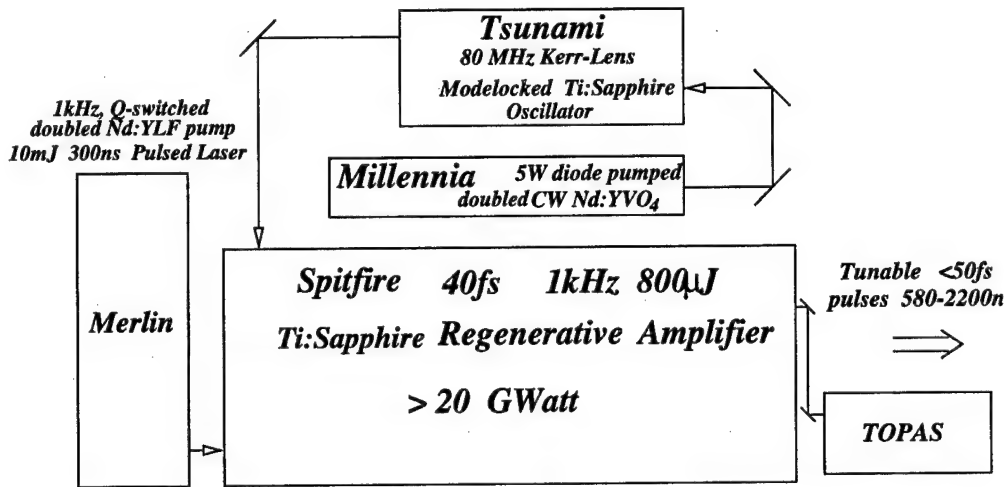


Figure 1: Layout of the tunable femtosecond system.

lens mode-locked Ti:Sapphire oscillator. The Tsunami mode-locked oscillator is pumped by a low-noise diode pumped doubled NdYVO₄ Millennia laser. The amplifier is pumped by Merlin, Q-switched NdYAG laser, which produces nanosecond pulses at a Kilo Hertz with an average power of 10W. Figure. 1 shows the layout of the system which produces tunable ultrashort pulses.

4.1 Ti:Sapphire Oscillator

Ti:Sapphire is a very broadband gain medium potentially capable of supporting temporal pulses which are close to few optical cycles centered around 800nm wavelength. Hence a properly designed dispersion compensated Ti:Sapphire oscillator can produce pulses in the femtosecond regime. Fourier transformation of the temporal train of ultrashort pulses produces an infinite spectral series. If the amplitudes of all these frequencies are phase locked, through mode-locking, they add up in phase resulting in a short pulse. The high intensity of the pulses produces Kerr-lens self-focussing inside the Ti:Sapphire crystal producing better pump beam overlap which sustains mode-locking by allowing high gain only for the short

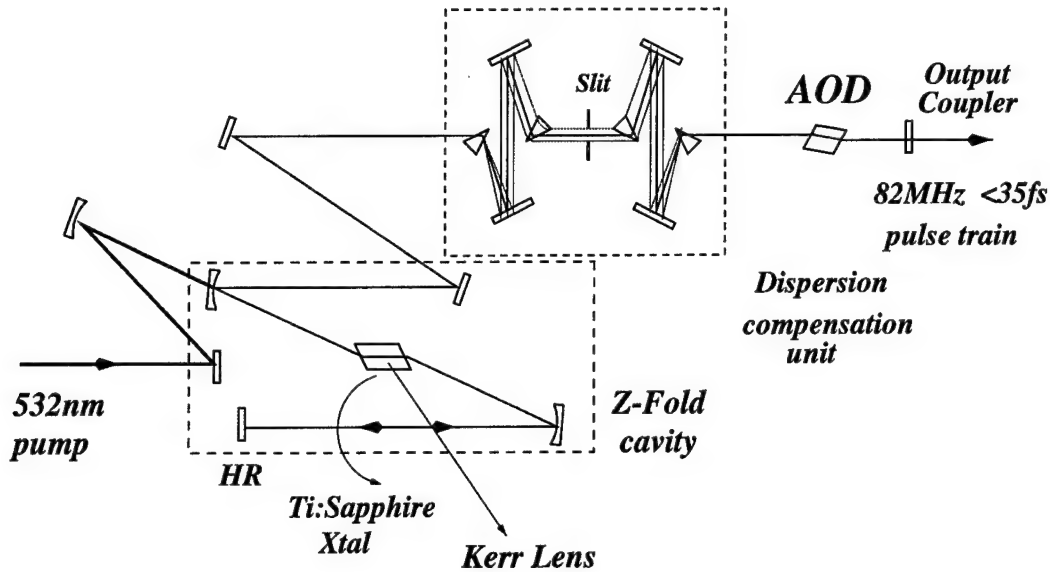


Figure 2: Schematic diagram of Tsunami sub 35fs Ti:Sapphire Kerr-lens mode-locked oscillator, with extended z-cavity. The four prism dispersion compensation setup can also allow spectral control for pulse temporal width adjustment. The acousto-optic device (AOD) is used to initiate and maintain the mode-locking operation.

pulses that selffocus. The laser crystal has a natural dispersive characteristics which tend to chirp and broaden short pulses traveling through the material. Material dispersion becomes more prominent for shorter pulses and requires a compensation mechanism, usually achieved by using a pair of prisms. Spectral components of the pulses are spatially dispersed and delayed differently to compensate for second order material dispersion in the laser crystal. This technique compensates for second order dispersion but cannot easily compensate for higher order dispersion and hence producing pulses shorter than 70fs becomes challenging. Choosing a material with the appropriate sign of $\beta^{(3)}$ allows even shorter pulses can be obtained.

The 35fs Tsunami (Fig. 2) from Spectra-Physics has four prism dispersive compensation and an acousto-optic mode-knocker to initiate and sustain kerr-lens mode-locked operation.

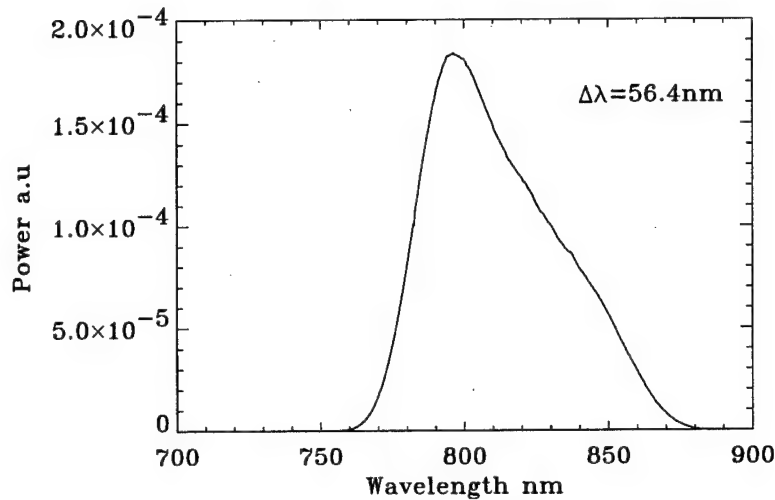


Figure 3: Spectrum of modelocked Ti:Sapphire laser.

The Tsunami produces 250mW average power 35fs pulses at a repetition rate of 82MHz, with an input pump power of 3.2W at 532nm. The laser cavity is built around an invar rod to be robust to temperature variations and suspended on Lee springs to counter any vibrational effects. The Tsunami is pumped by a low noise diode pumped doubled Nd:YVO₄ Millennia laser which lases at 532nm wavelength. The excellent beam pointing stability and the low noise of the Millennia results in good long term oscillator stability and sustainment of mode-locking over long durations with minimum oscillator alignment. With the current arrangement of the isolation of the thermal sources in a separate room away from the laser table we are able to achieve almost a day long uninterrupted mode-locked operation of the Tsunami.

4.2 Regenerative Amplifier

High peak power pulses can be obtained through amplification of the stable pulses from the Ti:Sapphire oscillator, which usually have nice spectral and temporal shapes, by using

the technique of chirped pulse amplification (CPA). In CPA seed pulses from the oscillator are stretched in time to about 400 picosecond from the original 35 femtosecond width, so that during the amplification process, the peak intensities inside the crystal are kept below the damage threshold of the amplifier. This also avoids unwanted nonlinear effects and preserves the spectral content and results in almost linear spectral amplification. Stretched pulses are injected in to the laser cavity by a pockel cell which changes the polarization of the pulse to the low loss polarization state acceptable by the cavity. From the turn on time of the first pockel cell, the pulse circulates in the cavity for about 10-20 round trips and picks up a gain which is roughly 10^6 . In amplifier Ti:Sapphire crystal is pumped by a Merlin, 1kHz Q-switched double Nd:YAG pulsed laser. Merlin produces pulses of about 300ns with high enough energy to pump a large volume of the Ti:Sapphire amplifier crystal allowing extraction of nearly 1mJ pulses. The total time spent by the pulses in the cavity and the pump pulse duration together fall within the radiative decay time ($3.2\mu\text{s}$) of the Ti:Sapphire lasing levels. After each round trip the seed pulses increase in energy and finally forces the laser in to the gain saturation regime (pulse reaches saturation fluence). At this point the cavity losses dominating so the timing is adjusted to eject the pulses of the cavity by reflecting of a thin film polarizer after changing its polarization state by switching 'on' an other pockel cell. This chirped high energy pulse is compressed by a grating compressor arranged for anomalous dispersion. The pulses in the regen cavity have $\geq 50\text{nm}$ of bandwidth and undergo considerable normal dispersion, which depends on the number of trips in the cavity. The grating compression can remove spectral chirp from both the stretcher and the amplifier crystal to second order, resulting in near transform pulses slightly broadened only by the higher order uncompensated dispersion.

Fig. 4 is a schematic of Spitfire regenerative amplification system in our lab that produces 44fs near transform limited pulses with $>800\mu\text{J}$ of energy per pulse at a repetition rate of 1kHz. The peak power of the pulse ($>20\text{GW}$) can easily result in several nonlinear interactions even with ordinary materials like glass which has a small nonlinear coefficients.

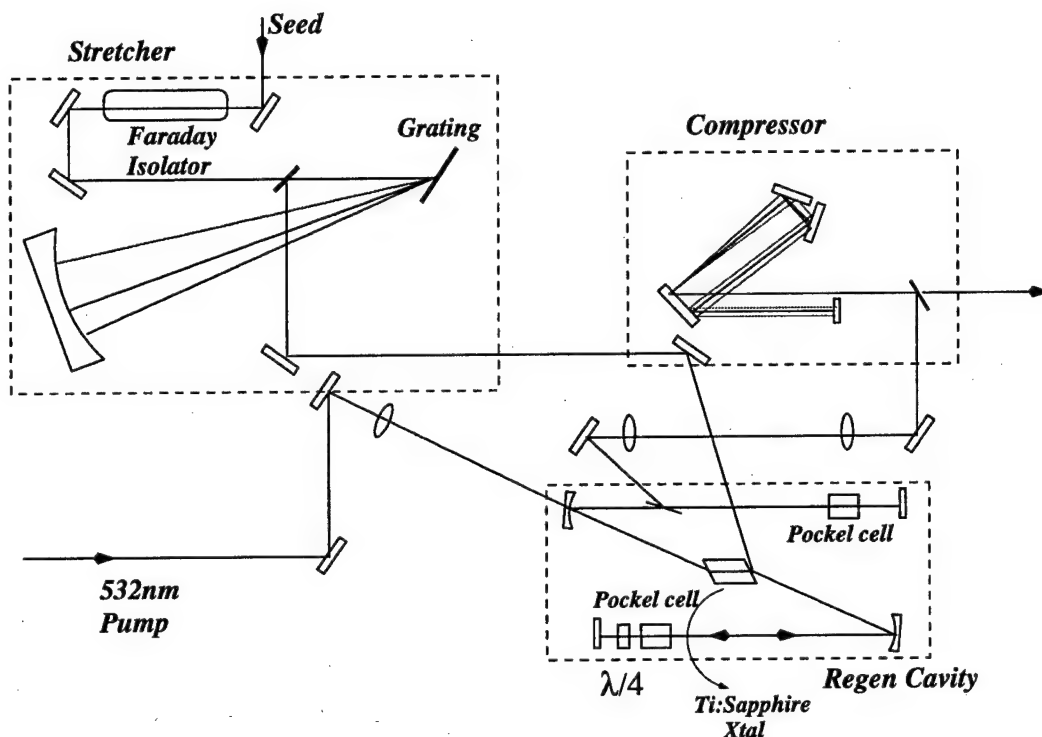


Figure 4: Schematic diagram of Spitfire sub 50fs Ti:Sapphire regenerative amplifier, with stretcher and compressor. Faraday isolator stops feedback of back propagating pulses in to the Tsunami. The 800 μ J, 44fs pulses at the output of the Spitfire form the pump source for TOPAS, (Traveling wave Optical Parametric Amplification by Superfluorescence)

Characterization of the pulse time-spectral profiles is very important in understanding, interpreting or controlling any nonlinear interactions. Section 5 presents the diagnostic tools we have in the lab for looking at pulses from the regenerative amplifier.

4.3 Travelling Wave Optical Parametric Amplification by Superfluorescence

Travelling wave Optical Parametric Amplification by Superfluorescence (TOPAS) is a $\chi^{(2)}$ based parametric 5 stage amplification system seeded by quantum noise generated super-

fluorescence. Generation of the seed and the amplification process are carried out in a single uniaxial non-centrosymmetric crystal β -Barium Borate (BBO). The system is pumped by the Spitfire 800 μ J single pulse. Unlike optical parametric oscillators (OPO), parametric generators (OPG) do not rely on optical cavity resonance for the generation and amplification of radiation. This allows a design with a very broad tuning range. In an intra cavity pumped OPO, usually only one of the two wavelengths (signal or idler) can be in resonance with the cavity. This reduces the tuning range allowed by such a system. However in a system with synchronous pumping, double resonance can be achieved but such a system produces train of pulses with relatively low energy per pulse. Hence OPGs are preferred over OPAs due to their wide tuning range. In OPGs, supercontinuum can also be used instead of superfluorescence however usually supercontinuum has spatial chirp associated with it, due to coupling between self-phase modulation and self-focusing which generate the continuum.

OPG is an ideal solution when the damage threshold of the crystal is higher than the parametric superfluorescence generation threshold (usually Gwatt/cm²). Quantum noise generated superfluorescence is usually weak, extremely broadband and needs high gain. Since the seed is weak, the amount of gain it can deplete is usually small to start with and hence only a weak portion of the pump pulses are used in the first three stages with the seed. Following this the appropriately delayed versions of fresh pump pulses amplify the subsequent stages which are run almost in saturation so that the output energy will remain constant. During the amplification stages, the pump pulse delay controls the overlap between the temporally chirped superfluorescence and the pump pulses as they propagate at different group velocities.

With an OPG both signal and idler can be amplified. At the output of the TOPAS, signal and idler wavelengths cover a spectral range from 1150nm to 2400nm. These outputs can be doubled with an external crystal to produce wavelengths from 580nm to 1150nm. Sum frequency with the pump pulses also produces some spectral coverage in the visible wavelength ranges.

TOPAS is completely automated to control the delays of the pump signals to the last

two stages and also the angles of the BBO crystals used for parametric amplification and the external SHG.

5 Pulse diagnostics

Since the pulses from most part of the laser system are extremely short and very broad spectral bandwidth, their accurate characterization is important for both alignment of the laser for regular functioning and for any nonlinear experiments. A common technique for pulse width diagnosis of ultrashort pulses is autocorrelation, which provides temporal width of pulses under certain assumptions on pulse shape. More advanced techniques include frequency resolved optical gating (FROG), for complete time spectral analysis and tilted pulse front autocorrelation (TFPA) for spatial-spectral analysis. The lab is equipped with several diagnostic tools including an Ocean Optics CCD based fiber spectrometer, an Ando scanning spectrometer, a scanning speaker cone and a rotating mirror autocorrelator, TFPA, polarization based FROG and a polarimeter.

5.1 Autocorrelator

Autocorrelation [1, 2, 3, 4, 5] is a widely used method of pulse width measurement. The pulse to be measure is split in to two which are temporally crossed in a nonlinear medium. There are several geometries which can be used. For laser sources with high rep-rates and low pulse energies, scanning geometries are preferred. Scanning geometry involves temporally scanning one pulse with respect to the other in a second harmonic medium. If the pulses are also perfectly spatially overlapped so that during scanning, their relative spatial phase results in spatially stationary fringes then an interferometric autocorrelation signal can be obtained. The interferometric signal is self calibrating in the sense the fringe count reveals the pulse width (assuming that center wavelength is known). On the other hand if the

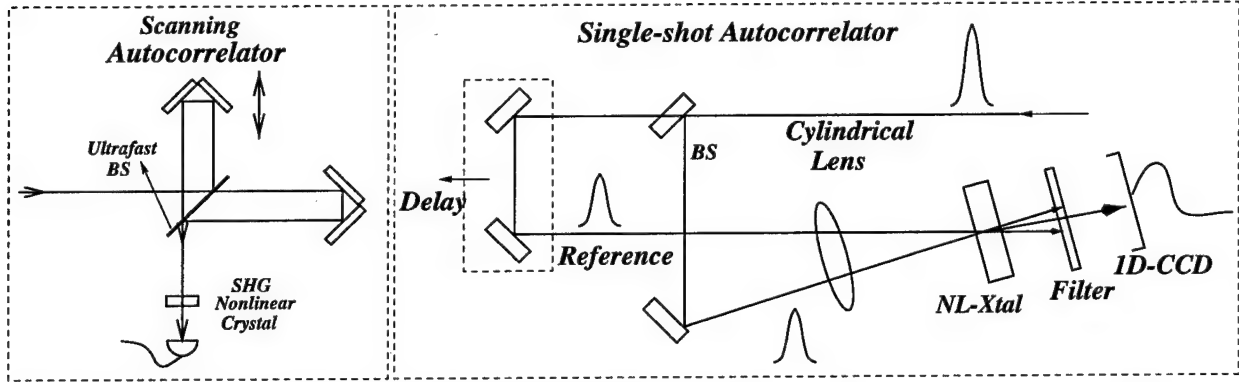


Figure 5: Commonly used autocorrelation geometries. Scanning method is preferred for low energy pulses, while single-shot technique is suitable for high energy pulses.

spatial overlap is not perfect, it results only in the envelope which is usually calibrated with a known delay inserted in to one of the delay arms. Autocorrelation cannot be deconvolved without any *a priori* information of the pulse shape, due to spectral phase ambiguity, as a consequence pre-pulses cannot be distinguished from post-pulses. Fourier transform of an autocorrelation trace gives the power spectrum. However when there are well characterized transform limited reference pulses available, cross correlation can be performed to obtain complete information about the second pulse.

5.2 Frequency Resolved Optical Gating

FROG [6, 7, 8] is a spectrally resolved autocorrelation or cross-correlation. In contrast to an autocorrelator which measures the signal-pulse-energy vs delay, FROG involves measuring the signal pulse spectrum vs. delay. In a self referenced geometry, the pulse to be measured is split into two replicas which are crossed in a nonlinear optical medium to create a signal field, as in autocorrelation. The signal pulse is then spectrally resolved. The signal

before spectrally resolving may be obtained by any autocorrelator or cross-correlator beam geometry by interacting the beams using any of several kinds of nonlinearities. However in spectrally resolved autocorrelation (second harmonic FROG) time direction ambiguities are not resolved. So instead we utilize the polarization-gate geometry which yields the most intuitive traces. The polarization-gate (PG) geometry for FROG shown in Figure 6.

In the PG FROG geometry, the two replicas of the pulse are usually called probe $E(t)$ and gate $E(t - \tau)$. The probe beam passes through crossed polarizers. The gate beam has its polarization rotated by 45 degrees, and overlaps the probe beam in the nonlinear optical medium (typically fused silica or glass). The gate beam induces a birefringence in the medium through the optical Kerr effect, which has the effect of rotating the probe beam polarization by a small amount when the pulses overlap in time. This results in some leakage through the crossed polarizers. This leakage is the signal field, and for a nearly-instantaneously responding medium has the form.

$$E_{sig}(t, \tau) = \chi^{(3)} E_x(t) |E_{45^\circ}(t - \tau)|^2 \hat{y} \quad (1)$$

Here, t is real time and τ is the time delay between the gate and probe beams which is proportional to the position and the sine of angle between the beams. This signal field is then frequency resolved by an imaging spectrometer, that is, its spectrum is measured at each position x . The spectrum of the signal field is measured for all relevant values of the delay time between the two beams to yield the FROG trace,

$$I_{FROG}(\omega, \tau) = \left| \int_{-\infty}^{\infty} dt E_{sig}(t, \tau) e^{i\omega t} \right|^2 \quad (2)$$

The time frequency spectrum from FROG is deconvolved using one of the standard 2D phase retrieval algorithms to obtain complete amplitude and phase information of the pulse [6, 9, 10]

Frequency Resolved Optical Gating

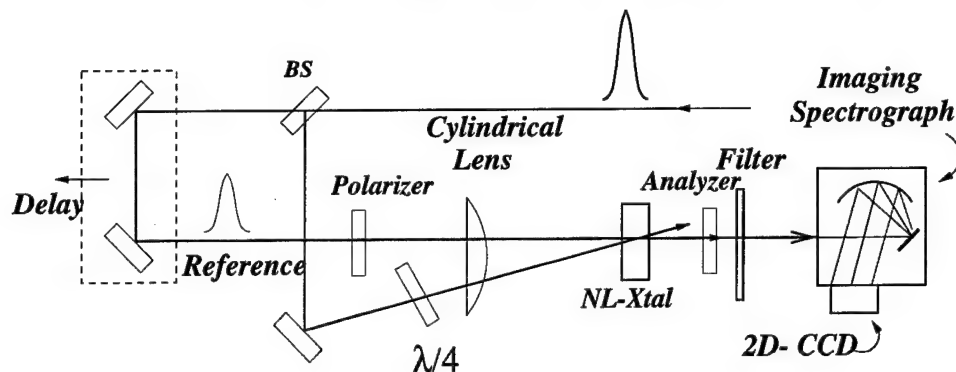


Figure 6: Schematic of polarization gating FROG. Two replicas to be measured are crossed in a nonlinear medium. One of the two pulses passes through two crossed-polarizers and is gated using the intensity of the second pulse. The resulting signal beam is spectrally resolved and detected.

5.3 Tilted Front Pulse Autocorrelator

The tilted front pulse autocorrelator (TFPA) [11] is a single shot correlation technique which involves correlating an image with its spatial parity flipped mirror replica. Advantage of such a correlation technique is that it reveals spatial variations of the spectral characteristics. A pulse with spatial-spectral non uniformity in the far field of the pulse can be viewed as a tilted pulse [11, 12]. Another convenient way of visualizing a tilted front pulse is a pulse with temporal delay across its spatial co-ordinate, as depicted in the inset of figure 7. Since such pulse tilts are produced by angular dispersive elements (prisms, gratings etc), such pulses in the far field will resolve in to spatial-spectral non uniformity due to uncompensated spatial dispersion. We can also expect phase matched nonlinear process to give rise to such pulses under strong frequency dependence of the phase matching conditions where different frequencies phase match better at different angles. Supercontinuum generated by focussing

a short pulse in to a Kerr material is usually associated with both spatial and temporal dispersions. Supercontinuum seeds used in parametric amplifiers can give rise to tilted pulses. Tilted pulses behave differently than normal pulses in nonlinear experiments [12, 13]. TOPAS is sensitive to tilted pulses since it has a long path length during the amplification stages. Tilted pulses can arise in the Spitfire amplifier if there is a nonzero relative angle between the compressor and the stretcher grating pairs. It can also arise from a single compressor if the subsequent passes through the grating are not exactly parallel. Light conversion ltd, TFPA is a version tailored specifically for short pulses from the regenerative amplifier, which can be used to align compressor grating of the Spitfire. Since there are not any spectrally selective elements in the system, it can be parked at a different center wavelength by tuning the phase matching crystal angle.

Figure 7 shows the optical implementation of TFPA. One of the pulse replicas traverses through odd number of mirror reflections resulting in spatial odd parity image in comparison to the second replica. And when both pulses cross inside the nonlinear crystal with a small enough angle in the vertical plane, there is a tilted pulse pattern due to second harmonic correlation which is created that lies in between two spots in the vertical line. The tilt of the signal in relation to the line defined by the two spots relate to the actual pulse tilt of the correlating pulses. The width in the dimension transverse to the tilted signal is related to the autocorrelation temporal pulse width of the pulses. So TFPA can yield both spatial-spectral and temporal information of the input pulses,

$$\tau = K \delta \frac{2n \sin(\phi/2)}{c} \quad (3)$$

where τ is the temporal FWHM, K is the pulse dependent form factor, n is the index of refraction of the nonlinear crystal, ϕ is the angle between the two correlating input signals

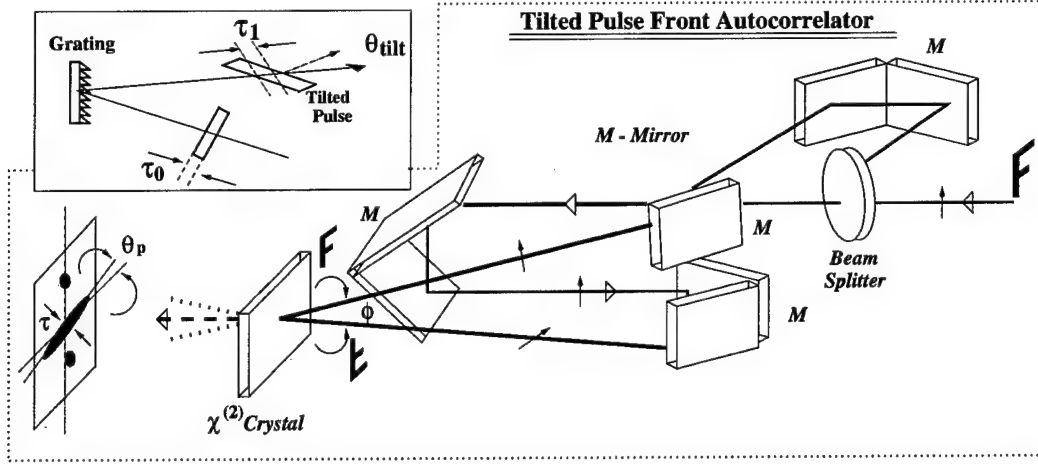


Figure 7: Inset of the figure shows an example of a tilted pulse generated by allow dispersive grating. The pulse in the far field is spectrally resolved. TFPA consists of two balanced arms which produce spatially flipped replicas of the input pulse which is later correlated inside a KTP crystal producing the second harmonic tilted signal.

and c is the velocity of light and

$$\tan(\theta_{tilt}) = \frac{c \cdot \tan(\theta_p)}{2k} \quad (4)$$

which relates the measured second harmonic tilted signal angle θ_p with the pulse tilt θ_{tilt} . Here the calibration constant k is calculated using the spatial shift Δx , of the SHG signal corresponding to a temporal shift Δt .

5.4 Linear Characterization and Instrument Automation

5.4.1 Spectrometers

For linear characterization we have Ocean optics spectrometer, Ando scanning spectrometer and ARC imaging spectrometer. Ocean Optics spectrometer is a low resolution fiber coupled CCD based spectrometer which works in visible and near IR (400nm-1000nm). The

spectrometer is useful for alignment of Kerr-lens modelocked oscillator and the Spitfire regen system. With the help of a doubling crystal the it is also helpful with TOPAS. The FROG system includes another imaging spectrometer with low dynamic range. However, for non-linear materials characterization we will require a much higher resolution, higher dynamic range, and wider wavelength range fully calibrated scanning spectrometer such as the Ando HP71450A. We also have an ARC3000 imaging spectrometer which can be used to convert a single shot autocorrelator to a FROG measurement. This spectrometer consists of toroidal grating for off-axis correction and can achieve good imaging resolution down to $10\mu\text{m}$.

5.4.2 Polarization Stokes Meter

A polarization Stokes meter provides the full vectorial characteristics of an optical beam. Thorlabs stokes meter works by the scanning the intensity variation of an input polarized beam after passing through a quarter wave plate and an analyzer. The stokes meter only requires only the wavelength of input beam for calibration.

5.4.3 Auto-Optics Motor Controller

Auto-Optics Motor controller is useful for automating optics alignment in systems like OPA, pulse compressor etc. It is also useful for experiments like Z-scan. Currently it capable of controlling 8 encoded motors, and can be further extended. The two axis motor controller can allow optimizations based on photo-detector signals.

6 Experiments

Current experiments in the lab focus on characterizing Kerr materials for all optical switching applications. Z-scan is used for nonlinear absorption and refraction measurements. Multidimensional soliton experiments for spatial dragging interactions are currently in progress.

6.1 The Z-scan technique

Z-scan [14, 15, 16] is a simple on axis scanning nonlinear refraction based technique which takes advantage of the modification of the spatial focusing properties of a converging Gaussian beam by the nonlinear index of the material. In Z-scan a nonlinear material whose refractive index is to be studied is scanned through the focus of a well defined converging beam. The technique can be used to determine both the nonlinear refractive index as well as the nonlinear absorption of the material without any sign ambiguity, provided the order of the nonlinearity is known *a priori*. Since the technique takes advantage of the spatial variation of the index profile, it can be used with both CW and pulsed laser beams. The technique does not reveal the exact time variation of the refractive index of the medium. However one can infer if the nonlinearity is time dependent or not by looking at both CW and pulsed Z-scans. For a material which is insensitive to the peak intensity and only depends on the integrated energy (such as slow thermal nonlinearity), Z-scan signal for CW or pulsed beam will look alike.

6.1.1 Nonlinear Refraction

Figure 8 shows a schematic diagram of a Z-scan experiment. The setup consists of a focusing lens, translation stage to scan the nonlinear medium through the focus and a detector at the far field placed on-axis with a small slit before it. As the sample scans through the focus depending on the sign of nonlinearity and the position of the material with respect to the focus, the beam is either focussed or defocussed. Because of the intensity dependence of the refractive index ($n = n_0 + n_2 I$, n_2 is referred to as Kerr index and I is the on-axis irradiance in the material.), the spatial index variation of the medium as the laser beam travels through it mimics the local spatial intensity variation of the traveling pulse. This is similar to intensity dependent lens formation. When the sample is right at the focus the

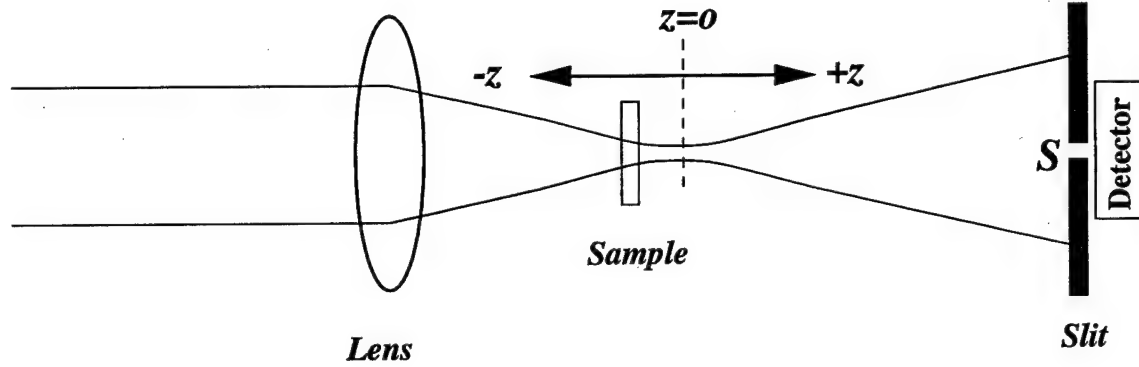


Figure 8: Z-scan experimental setup for the determination of nonlinear refractive index. Nonlinear sample is scanned through the focus of the lens and the signal from a detector placed in the far field is recorded. S is the ratio of the aperture to the beam width in the far field.

lens formed has no effect in the far field pattern, hence the signal resembles the background at the focus ($z=0$). For a self-focusing medium (positive n_2), as the material scans the focus from $-z$ to $+z$, the signal at the detector undergoes a valley to peak transition. A self-defocussing medium shows a peak-valley signal. Thus the sign of the index nonlinearity is directly inferable from the Z-scan measurement. The peak to valley height (ΔT_{p-v}) of a background normalized signal is related to the nonlinear phase change ($\Delta\Phi_0$) of the traveling laser beam. For a Kerr medium this is given by

$$\Delta T_{p-v} \simeq 0.406(1 - S)^{0.25} |\Delta\Phi_0| \quad (5)$$

Where S is the aperture ratio at the detector. The above equation is accurate within 2% for Gaussian input beam focusing through the lens producing $\Delta\Phi_0 < \pi$. For small aperture ratio, the term $(1 - S)^{0.25}$ is nearly unity and can be neglected. The on-axis phase shift $\Delta\Phi_0(t)$

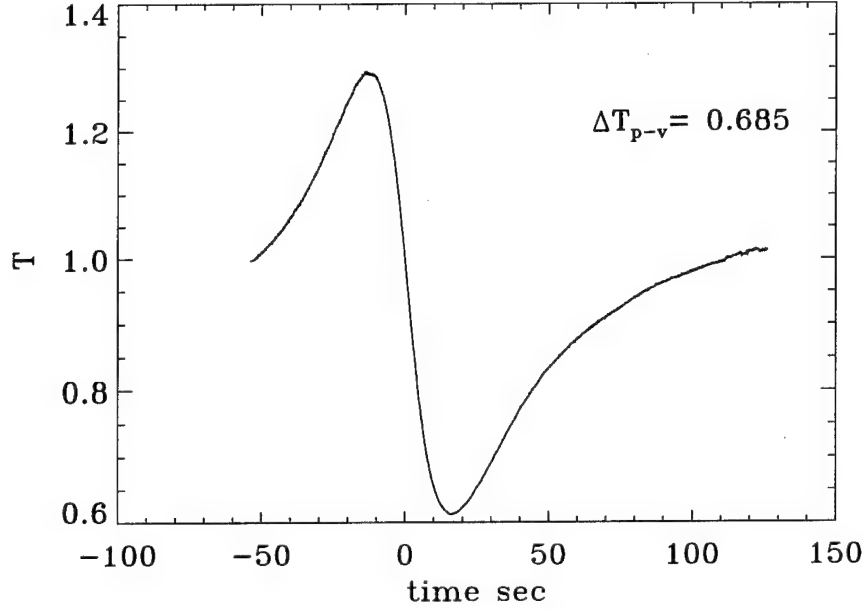


Figure 9: Experimental Z-scan trace with $S < 0.1$ using modelocked Ti:Sapphire laser pulses, on a $10\mu\text{m}$ thick discotic liquid crystal sample. An average power of 242mW is used in the experiment.

at the focus for a Gaussian beam is related to the refractive index variation according to

$$\Delta\Phi_0(t) = k\Delta n_0(t)L_{eff} \quad (6)$$

Where $L_{eff} = \frac{(1-e^{-\alpha L})}{\alpha}$ is the effective length of the material taking into account the correction due to linear absorption α . From the index variation $\Delta n_0(t) = \frac{\gamma}{2} |E|^2 = n_2 I$. E is peak electric field (cgs) and I is peak irradiance in MKS (n_2 and γ are related by $\gamma \text{ (esu)} = \frac{cn_0}{40\pi} n_2 \text{ (m}^2/\text{W})$).

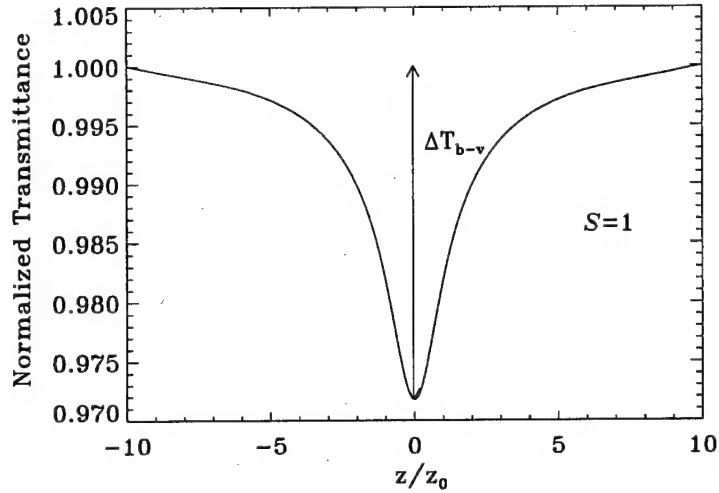


Figure 10: Calculated absorption trace for a material with $q_o(0,0) = 1$. The valley depth ΔT_{b-v} can be used to calculate the nonlinear absorption of the medium.

6.1.2 Nonlinear Absorption

Z-scan performed with the aperture completely open ($S = 1$) contains information about nonlinear absorption. At the focus due to higher intensity, the absorption is higher in comparison to other portions of the scan. Normalized transmittance for a Gaussian beam can be derived to be

$$\Delta T_{b-v} = \left| 1 - \frac{1}{Q_o} \ln(1 + Q_o) \right| \quad (7)$$

where $Q_o = \beta I_0 L_{eff}$. This equation is correct to all orders. The background to the valley data from the nonlinear absorption plot can be used to obtain the nonlinear absorption coefficient β directly knowing the effective crystal length L_{eff} . Figure 10 shows a calculated absorption plot. The plot can be seen to be even symmetric about $z=0$, since the nonlinear absorption

is only dependent on the local intensity of the pulse rather than the phase.

6.2 2+1D Spatial Soliton Dragging Logic

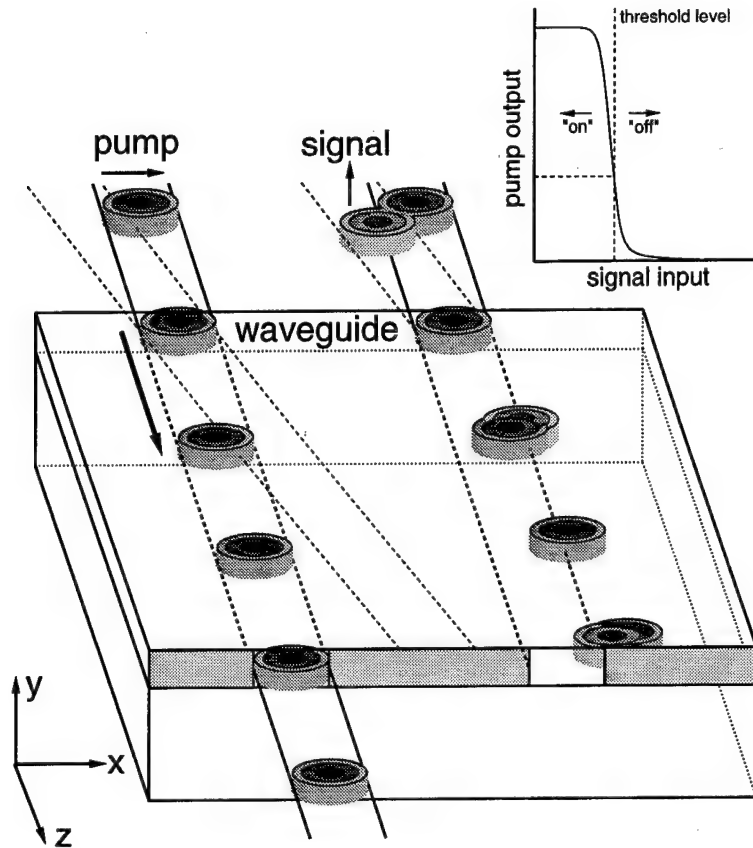


Figure 11: 2+1D Spatial soliton dragging logic gate. Spatio temporal pump soliton emerges out of the device in absence of a signal beam. In the presence of a signal beam, the pump is spatially dragged and clipped to produce “off” state of the device. The controlled NOT can be extended to a NOR gate.

Our research in ultrafast NLO is motivated by the application of optical soliton logic. Our approach is based on Spatial soliton dragging logic devices in which two orthogonal solitons in a planar waveguide geometry interact such that a weak signal can turn off a strong pump by dragging it to the side so it misses a small output pinhole [17]. A simple picture illustrating the working of such a device is shown in Fig. 11. The switching device is essentially a planar nonlinear medium sandwiched between two cladding layers for transverse guiding of light and a decision making aperture at the exit face of the waveguide. A pump soliton when launched in to the switch propagates without diffraction along the length of the waveguide then passes through the aperture and emerges at the output of the device. However in the presence of an initially overlapping orthogonally polarized weak signal beam traveling at a small angle, the solitons interact by the change in the refractive index produced due to the cross-phase modulation term and drag each other and for small angles they will form a single beam bound state obeying the momentum conservation. A few confocal lengths of such an interaction results in enough lateral shift of the pump beam comparable to its spatial width and so that it will fully miss the output pinhole aperture, yielding a low output. This is a controlled NOT interaction, which can be extended to universal NOR gate operation in the presence of multiple signal beams, or in a cascaded geometry.

The above device was extensively studied by our research group [18, 19]. Numerical and theoretical studies show that under cubic-quintic nonlinear index saturation, stable multi-dimensional solitons can be supported in nonlinear media. Spatial dragging interaction between solitons is an efficient scheme which allows easy hard spatial thresholding as opposed to temporal dragging and it also satisfies all the requirements for building cascable logic devices. This encourages to consider switching scheme for logic which is based on spatial interaction between ultrashort pulses so that the device can be temporally pipelined to achieve speeds approaching 10THz. However under very short pulse conditions several additional corrections need to be considered to the vector nonlinear Schroedinger equation. One of the main concerns for extremely short pulses is the nonresonant Raman interaction

which results in spectral downshift. In addition, several higher order temporal derivative nonlinear terms can effect what would otherwise be soliton like propagation. These effects have been numerically and with the help of multiple-scales analysis of the extended NLS. The results from such detailed simulations show that cascable logic device can still be built even in materials like ordinary glass.

Current research in the lab is focussed towards experimentally verifying several of these numerical predictions. Our initial efforts are channeled towards building slab waveguides and we are looking for the existence of multidimensional spatio-temporal solitons. In focusing to a waveguide with a think lens, these ultrashort pulses change there shape due to dispersion and other abberations. Some of these can be precompensated by pulse shaping techniques. We have built the waveguides and are currently in the process of testing their linear and nonlinear guiding properties at $1.55\mu\text{m}$.

7 Conclusions

An ultrafast amplified and tunable laser facility was developed along with the spectral, temporal, spatial, and polarization characterization equipment to allow a wide variety of nonlinear optical spectroscopy and spatio-temporal optical soliton experiments for switching.

The system is capable of producing sub 50fs pulses at 1KHz repetition rate at nearly 1mJ of energy at 800nm. Through optical parametric amplification and frequency doubling we can produce sub 50fs pulses tunable from 580nm-2200nm. The construction of the state-of-art facility was possible due to the support of the DURIP program, a parallel AFOSR grant in spatio-temporal soliton switching and with the matching money from the University of Colorado.

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